Characterization and Compensation of the Atmosphere for the Inversion of AVIRIS Calibrated Radiance to Apparent Surface Reflectance

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ABSTRACT

Calibrated radiance spectra measured remotely record the integrated effects of the solar source, the atmosphere, and the surface. To pursue scientific research and applications, based on the molecular absorptions and constituent scattering properties of the surface, the solar source and atmosphere must be characterized and compensated in the spectra. This paper describes a set of radiative transfer spectral fitting algorithms that characterize the absorbing and scattering constituents of the atmosphere from calibrated AVIRIS spectra. These atmospheric characteristics were used in conjunction with the illumination and observation geometries to invert the AVIRIS calibrated radiance spectra to apparent surface reflectance. A validation of the algorithm was performed with in-situ reflectance spectra acquired at the time of the AVIRIS overflight over Pasadena, California, in 1994.

INTRODUCTION

Remotely measured data from satellites and aircraft are essential to support the measurement and monitoring of Earth surface processes over a range of spatial and temporal scales. In the solar reflected portion of the spectrum, the data acquired at the sensor are a record of the integrated effects of the solar source, the atmosphere, and the surface. A set of algorithms was developed to characterize and compensate for the atmospheric effects in the calibrated spectra acquired by AVIRIS. AVIRIS measures the solar reflected spectrum from 400 nm to 2500 nm at 10-nm intervals from 20 km altitude in the Q-bay of a NASA ER-2 aircraft. These spectra are acquired as images of 11 km by up to 100 km with 20-m by 20-m spatial resolution. AVIRIS is calibrated in the laboratory and the calibration is validated in flight (Conel et al., 1988; Green et al., 1988; Green, 1990; Green et al., 1993; Green and Conel, 1995).

Algorithms were developed to characterize the water vapor, well-mixed gases, molecular scattering, and aerosol scattering from calibrated spectra acquired by AVIRIS. The atmospheric characteristics were used to invert the AVIRIS measured radiance to apparent surface reflectance. These algorithms rely on the atmospheric models of the MODTRAN3 radiative transfer code (Kneizys et al., 1987; Berk et al., 1989; Anderson et al., 1995). MODTRAN3 was used in conjunction with the downhill simplex nonlinear spectral fitting algorithm (Press 1986) to invert for the atmosphere characteristics. The comparison of MODTRAN3 and AVIRIS spectra from the 1994 in-flight calibration experiment was used to link the calibration of AVIRIS to that of MODTRAN3. This paper describes the application and validation of these algorithms to an AVIRIS data set acquired over Pasadena, California.

MEASUREMENTS

AVIRIS acquired a data set of the total spectral upwelling radiance over the Pasadena, California, region at 18.55 UTC on April 11, 1994. The latitude and longitude of the Rose Bowl contained in the data set is 34.16° latitude and -118.33° longitude. Figure 1 shows a single wavelength image from the AVIRIS data set. The Jet Propulsion Laboratory is in the center left of the image and the Rose Bowl is located at the lower left. Mount Wilson is located at the upper center of the image. An AVIRIS radiance spectrum from the Rose Bowl parking lot and adjacent grass field is shown in Figure 2. At the time of the AVIRIS overflight, surface spectra's reflectance measurements were acquired in the Rose Bowl parking lot and adjacent grass field. These are shown in Figure 3. Comparison of the AVIRIS measured radiance and in-situ reflectance measurement shows the effect of the solar source and atmosphere in the total upwelling spectral radiance measured by AVIRIS.

Figure 1. April 11, 1994, AVIRIS image of Pasadena, California.

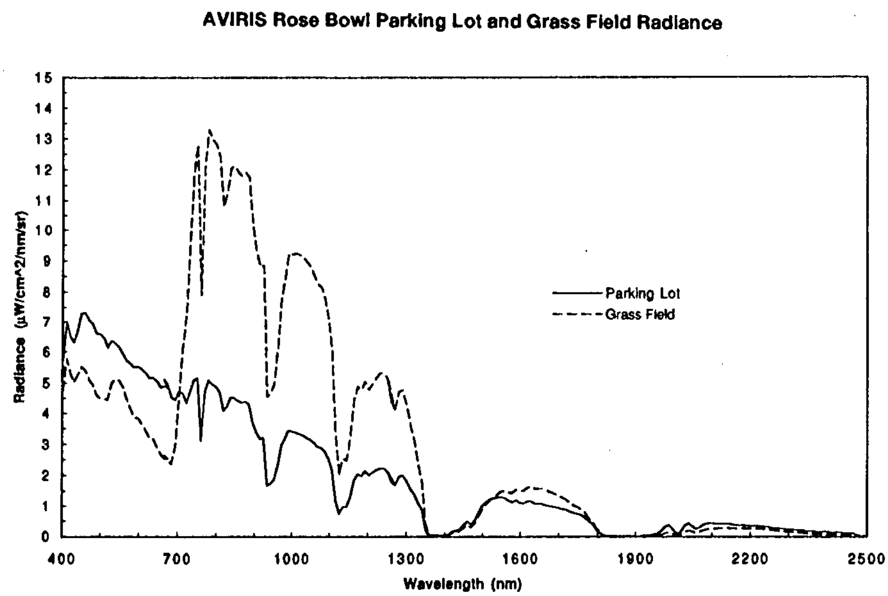

Figure 2. AVIRIS spectra of the total upwelling radiance for the Rose Bowl parking lot and adjacent grass field.

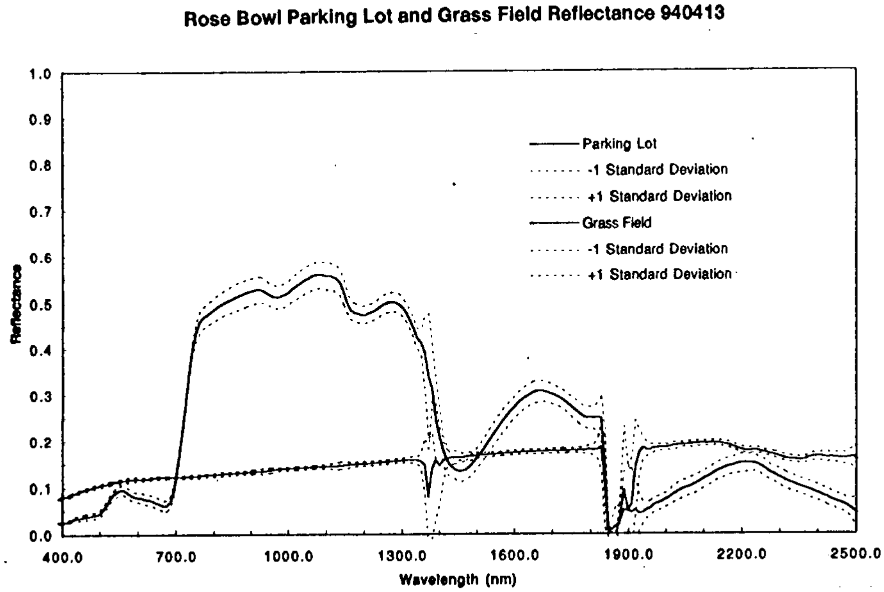

Figure 3. In-situ measured surface reflectance at the Rose Bowl at the time of the AVIRIS overflight.

ANALYSIS

AVIRIS calibration

In 1994 the AVIRIS in-flight calibration experiment (Green and Conel, 1995), a comparison of MODTRAN3 predicted radiance and AVIRIS measured radiance showed AVIRIS calibrated better than 95%. However, in detail, the residual 5% disagreement is spectrally featureful as shown in Figure 4. These spectral differences were attributed to errors in the MODTRAN3 model of the atmosphere. The ratio of AVIRIS to MODTRAN3 was used as an additional calibration factor to compensate for these errors. In addition, the AVIRIS sensor performance changed slightly from the time of the calibration experiment to the time of the Pasadena data acquisition. This variation in performance is shown in Figure 5 and was used to calibrate AVIRIS performance to that of the in-flight calibration experiment.

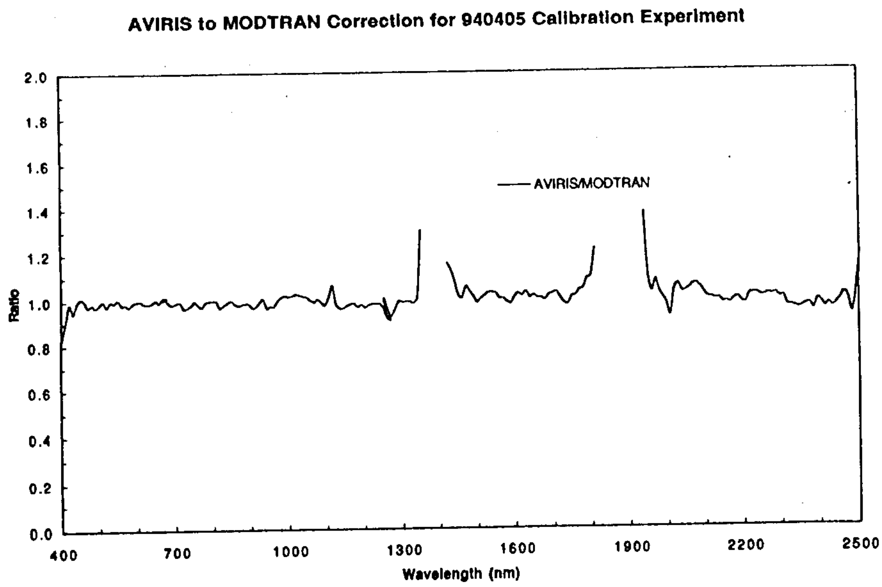

Figure 4. Calibration ratio between AVIRIS and MODTRAN3 derived from the in-flight calibration experiment on April 4, 1994.

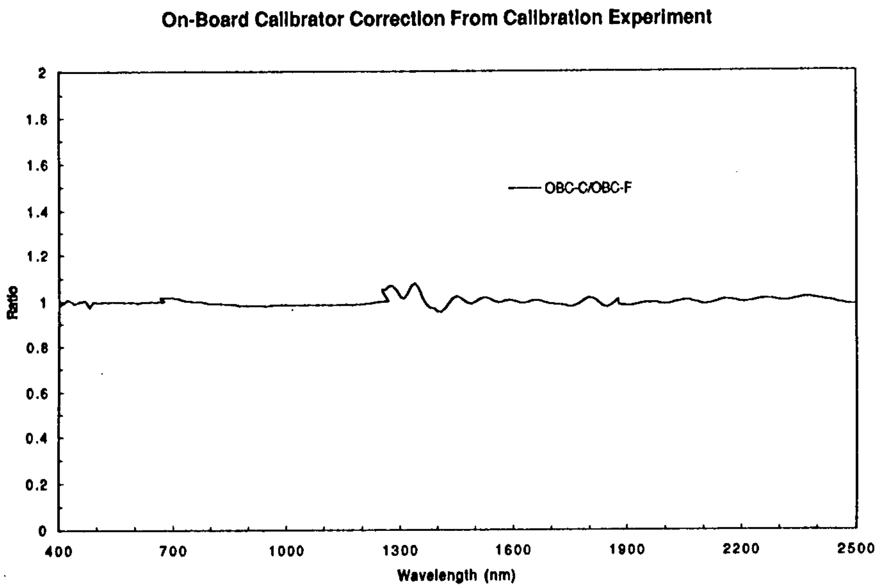

Figure 5. Calibration ratio of the onboard calibrator signal for the Pasadena flight to the signal for the in-flight calibration experiment.

Surface Pressure Height

The radiance measured by AVIRIS is affected by the absorption and scattering due to the well-mixed gases of the atmosphere (e.g., carbon dioxide and oxygen). To characterize the well-mixed atmospheric gases and the effect of atmospheric molecular scattering, an algorithm was developed to estimate the surface pressure elevation from the AVIRIS measured radiance. This algorithm assesses the strength of the 760-nm oxygen absorption band measured in the AVIRIS spectrum (Green et al., 1991; Green et al., 1993). The oxygen-band strength is calibrated to surface pressure elevation using the oxygen-band model in the MODTRAN3 radiative transfer code. Figure 6 shows the AVIRIS-derived image of surface pressure height for the Pasadena data set. Pressure heights range from 50 to 1900 m and correspond generally to the topographic elevation. The sensitivity of AVIRIS to the oxygen pressure height is moderate. To enhance the AVIRIS precision, a 5-by-5 spatial-sample average was used. The resulting precision is estimated at 200 m.

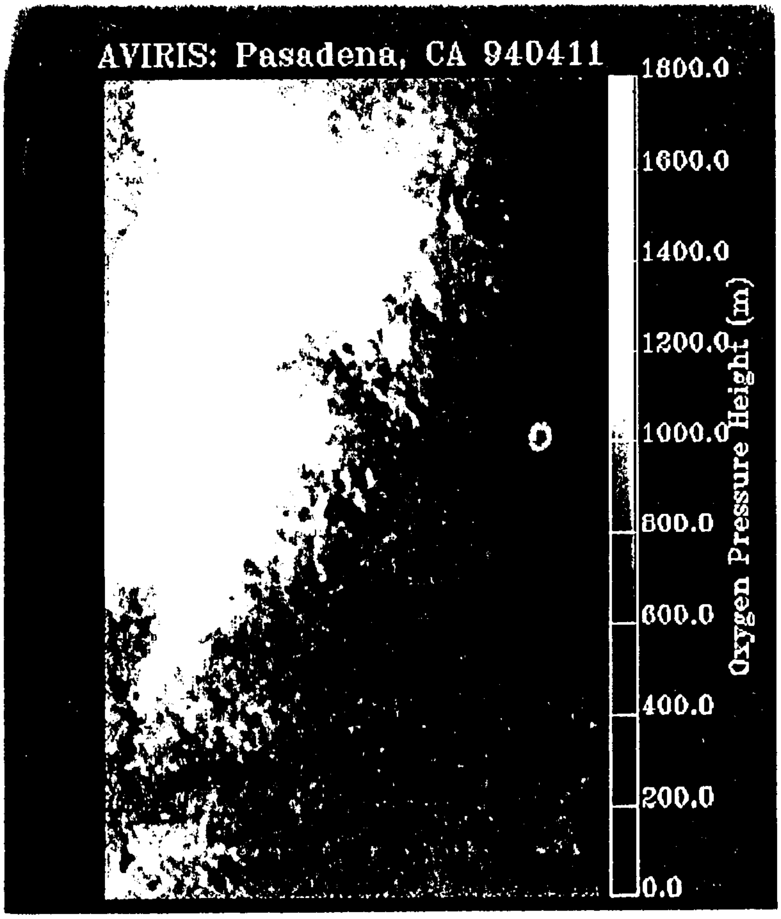

Figure 6. AVIRIS-derived surface pressure height for Pasadena data set.

Aerosol Optical Depth

The spectral radiance incident at AVIRIS is affected by scattering in the atmosphere due to aerosols. The effect of aerosol scattering is strong in the 400-nm to 700-nm region and increases towards shorter wavelengths. A nonlinear least-squares spectral fitting algorithm was developed to estimate the aerosol optical depth directly from the AVIRIS measured radiance. This algorithm optimizes the fit between the AVIRIS radiance and a MODTRAN3 modeled radiance with the aerosol optical depth as the primary fitting parameter. A MODTRAN3 model atmosphere must be initially selected. Parameters describing the reflectance magnitude, reflectance spectral slope, and the leaf chlorophyll absorption were included. Surface pressure height is used as a constraint. The algorithm was applied to the Pasadena AVIRIS data set using the MODTRAN3 urban atmospheric model. Figure 7 shows the spectral fit and derived aerosol scattering presented as visibility in km for the Rose Bowl parking lot. Figure 8 shows the aerosol visibility for the AVIRIS Pasadena data set. To improve the uniformity of the estimated aerosol effect, the data were averaged over 11-by-11 spatial elements. Derived visibility ranged from 40 km to 140 km. The trend of greater visibility at high elevations and less visibility at lower elevations is consistent with the expected distribution of aerosols in the Pasadena region.

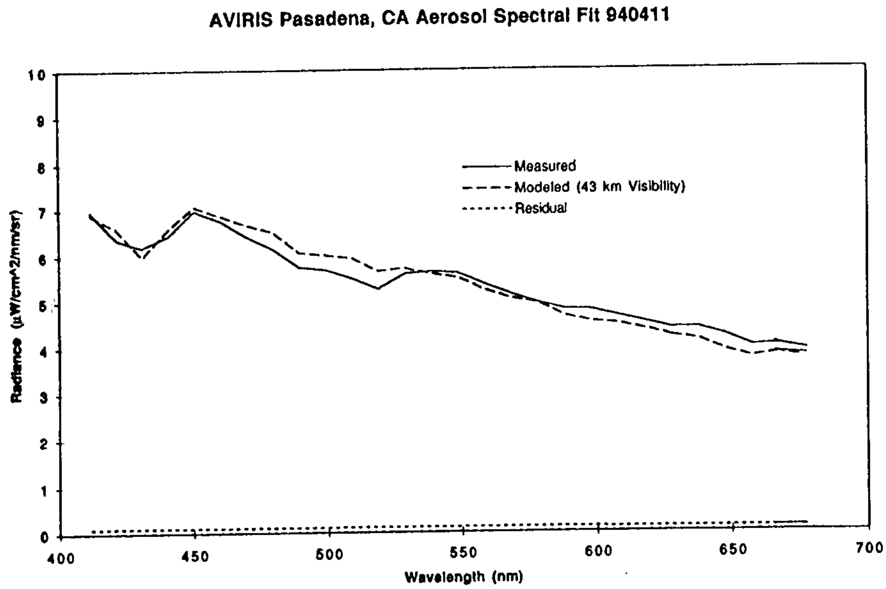

Figure 7. Spectral fit for aerosols at the Rose Bowl parking lot.

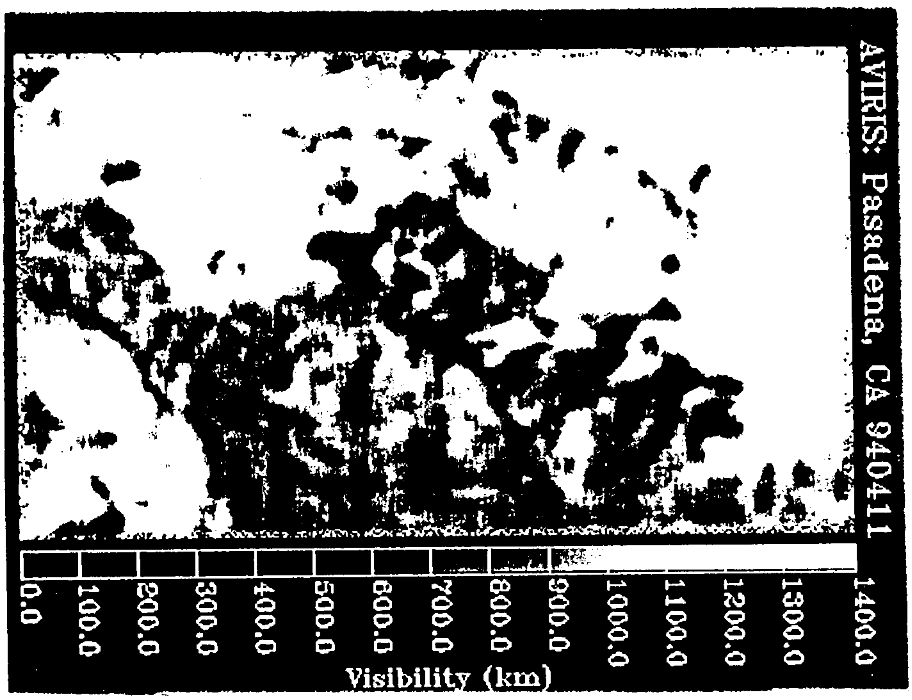

Figure 8. Image of derived aerosol expressed visibility for the MODTRAN3 urban aerosol atmospheric model.

Water Vapor

Across the AVIRIS spectral range, the strongest atmospheric absorber is water vapor. The effect on the upwelling radiance arriving at AVIRIS is shown in Figure 9 as the atmosphere varies from 0 to more than 36.5 precipitable mm of water vapor. In addition to absorbing strongly, water vapor in the terrestrial atmosphere varies both spatially and temporally (Green et al., 1991, Green and Conel, 1995).

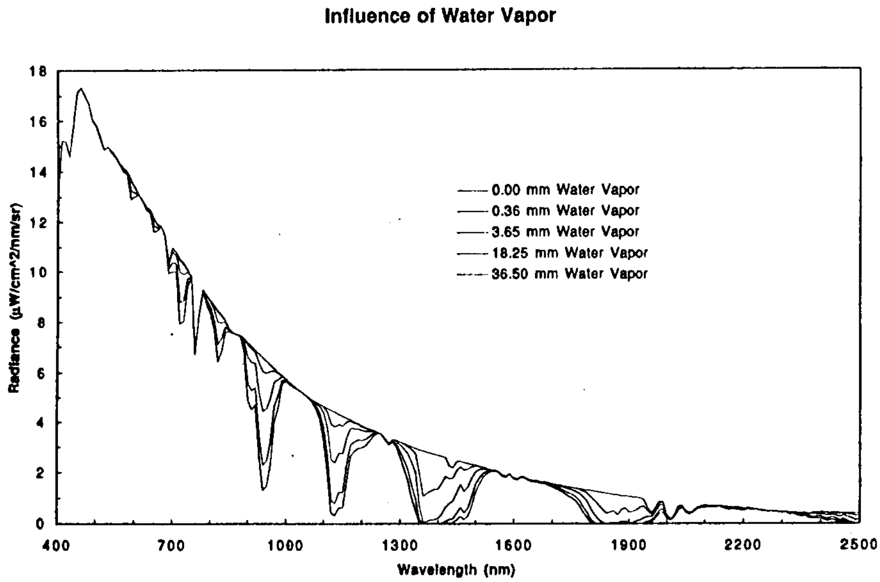

Figure 9. Influence of water vapor on the upwelling spectral radiance measured by AVIRIS.

To compensate for water vapor absorption in AVIRIS spectra, a determination of total path water vapor is required for each spatial element. Water vapor algorithms for AVIRIS have been developed (Conel et al., 1988; Green, 1991; Green and Conel, 1995) based initially on the LOWTRAN (Kneizys et al., 1987) and currently on the MODTRAN3 (Berk et al., 1989, Anderson et al., 1995) radiative transfer code. Alternate approaches for characterization of the atmospheric water vapor have been pursued (Gao and Goetz, 1990).

The water vapor algorithm used here fits the AVIRIS measured radiance for the 940-nm water band to a radiance spectrum MODTRAN3. In addition to a parameter controlling water vapor, the spectral fit includes a three-parameter surface reflectance model with leaf water. Inclusion of leaf-water absorption is essential to achieve good fits over vegetated surfaces. This algorithm was applied to the AVIRIS Pasadena data set. Figures 10 and 11 show the fits for the Rose Bowl and Mount Wilson spectra, respectively. Values of 9.87 and 3.42 mm were derived. The water vapor image for the entire data set is shown in Figure 12. Total column water vapor amounts were derived from 3.19-mm to 10.22-mm across the Pasadena image. The changes in the atmospheric path length due to elevation are strongly expressed in this result.

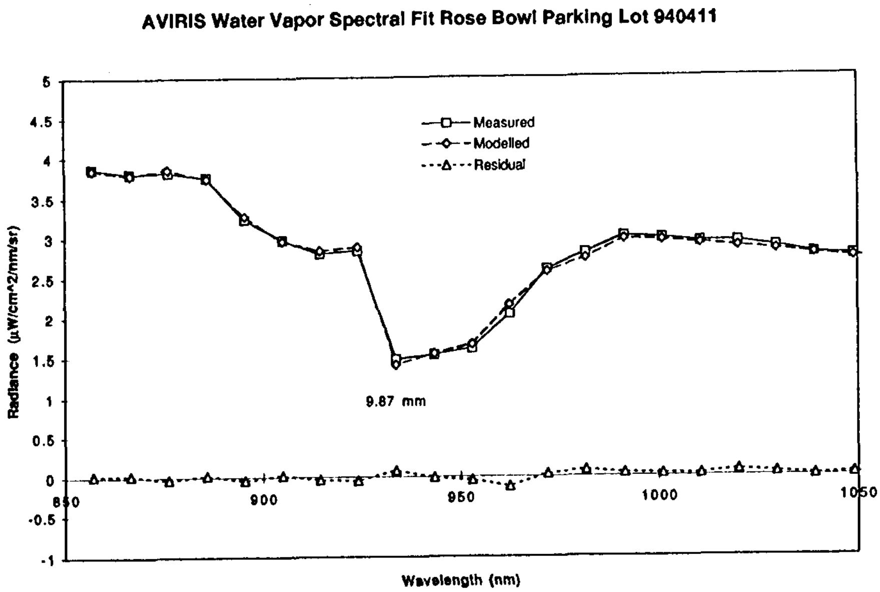

Figure 10. AVIRIS water vapor spectral fit for the Rose Bowl parking lot.

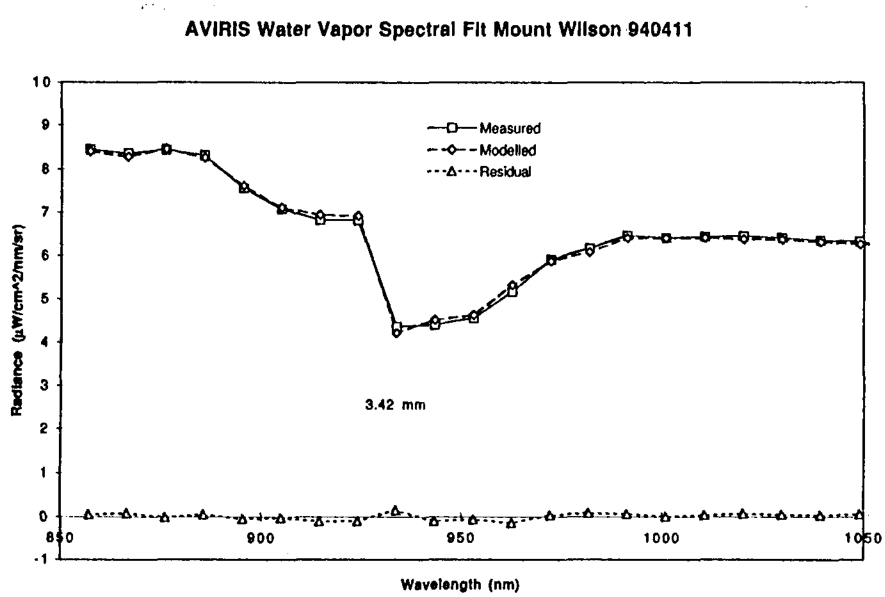

Figure 11. Water vapor spectral fit at Mount Wilson.

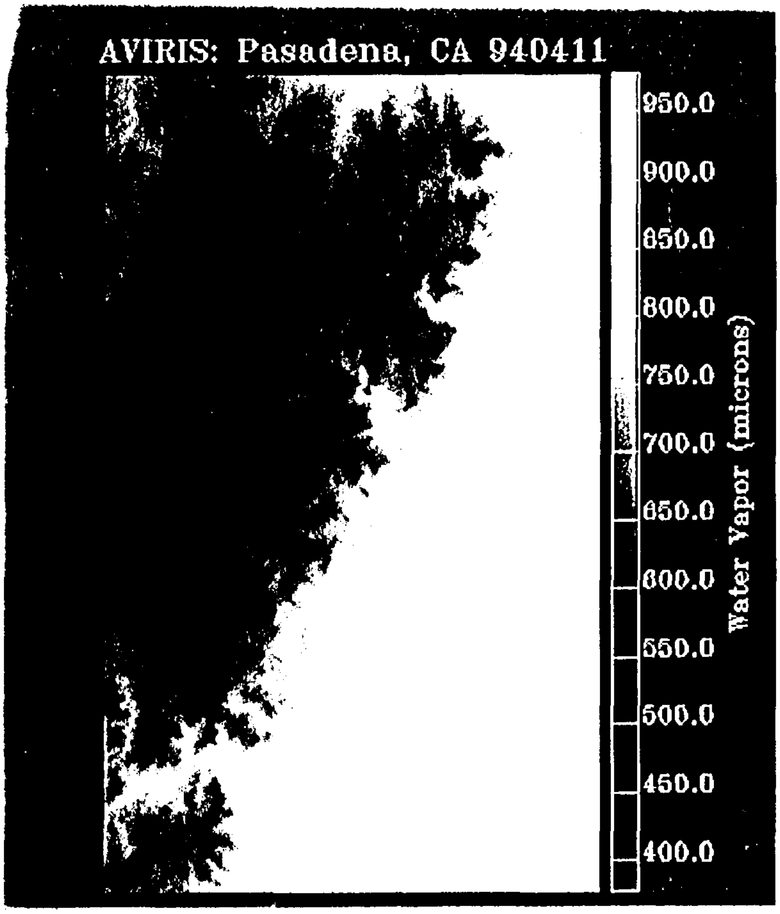

Figure 12. Water vapor image of Pasadena region from AVIRIS.

Radiance to Reflectance Inversion

Calculation of surface spectral reflectance from the total upwelling radiance measured by AVIRIS using a radiative transfer code has been pursued since the flights of AVIRIS in 1989 (Green, 1990, Green et al., 1991; Green et al., 1993). A related method for radiance-to-reflectance inversion (Gao et al. 1993) was pursued with AVIRIS data. In direct comparisons (Clark et al., 1995) the MODTRAN-based algorithm showed superior results.

The total upwelling spectral radiance at the top of the atmosphere in the observation direction may be expressed in terms of the solar illumination of a lambertian reflectance surface (Chandrasekhar, 1960). For a given illumination and observation geometry as well as atmospheric absorption and scattering characteristics, this relationship is given as:

$$L_t = F_0 r_a/p + F_0 T_d\, r_g T_u/p/(1-Sr_g) \qquad (1)$$

where L_t is the total upwelling spectral radiance at AVIRIS, F_0 is the exoatmospheric solar irradiance, r_a is the atmospheric reflectance, T_d is the downward direct and diffuse transmittance of the atmosphere, r_g is the apparent lambertion surface reflectance, T_u is the upward total atmospheric transmittance to the AVIRIS, and S is the albedo of the atmosphere above the surface.

This equation may be solved for r_g:

$$r_g = 1 / [\{(F_0 T_d T_u/p) / (L_t - F_0 r_a/p)\} + S] \qquad (2)$$

Using the water vapor, pressure elevation, and aerosol optical depth estimations derived in the algorithms described, the two-way transmitted radiance and atmospheric reflectance were calculated for each spatial element with MODTRAN3. A recent compilation of the exoatmospheric solar irradiance was used (Green and Gao, 1993). Computer look-up tables were used to accelerate MODTRAN3 calculations. With these determined parameters, the surface reflectance was calculated as shown in Equation 2. Figure 13 shows a comparison of the AVIRIS-derived reflectance for the Rose Bowl parking lot and adjacent grass field. The solar source and atmospheric effects present in the measured upwelling spectral radiance are compensated for with this algorithm. Also shown are in-situ reflectance measurements acquired for these surfaces 3 days after the AVIRIS flight. The effects of the average agreement between the derived and measured reflectance are 5.6 % and 9.4 % for the parking lot and grass field, respectively.

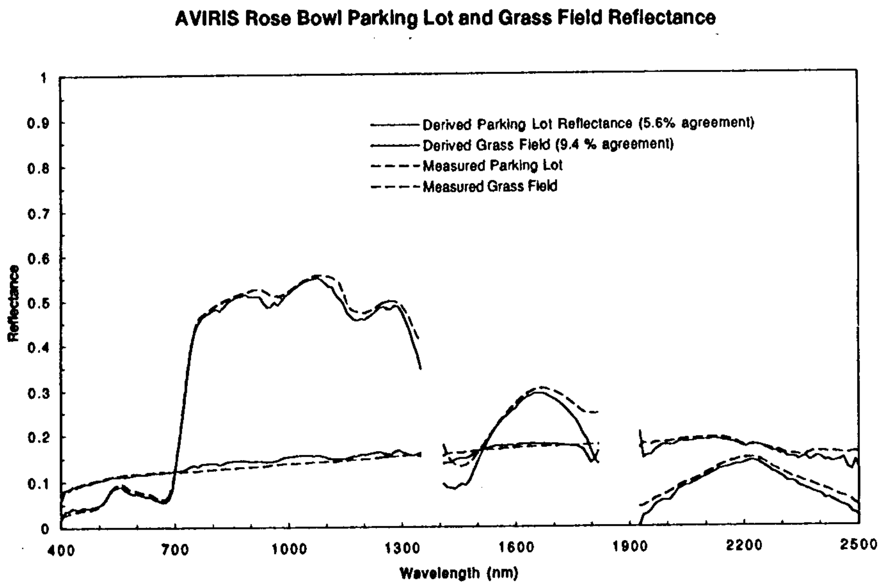

Figure 13. Inversion results for AVIRIS radiance to apparent surface reflectance for the Rose Bowl parking lot and adjacent grass field.

CONCLUSION

Algorithms were developed and used to characterize the surface pressure height, aerosol scattering, and atmospheric water vapor from calibrated AVIRIS spectra. The algorithms used in the MODTRAN3 radiative transfer code model of the atmospheric absorption and scattering are coupled with a nonlinear least-squares fitting algorithm. AVIRIS calibration was augmented to account for the current residual disagreement between AVIRIS and MODTRAN3 measured and modeled radiance based on an in-flight calibration experiment. These algorithms were applied to a data set acquired over Pasadena, California, on April 11, 1994. An equation relating the apparent surface reflectance to the total upwelling spectral radiance for a given atmosphere and illumination geometry was described. This equation was constrained by inputs of the derived atmospheric absorption and scattering characteristics to MODTRAN3. Apparent surface reflectance was derived for the complete AVIRIS data set. Solar source and atmospheric effects were compensated in the derived apparent reflectance spectra. At the Rose Bowl parking lot and adjacent grass field, the derived apparent reflectance was compared with in-situ measurements. An agreement of 5.6 % and 9.4 % was shown, providing an end-to end validation of the algorithm. Physically based derivation of the apparent surface spectral reflectance from calibrated upwelling radiance using only the spectra themselves is essential for research and application that are based on absorption and scattering characteristics of the surface.

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